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DSTL, WO 189/905, 17 Jun 2009

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20 MAR 1957	
57C378	

PERMANENT MAGNET COUPLINGS FOR GLANDLESS ROTARY DRIVES

By

W. G. SAUNDERS AND F. H. DODD

PORTON TECHNICAL PAPER No. 582

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SUMMARY

A short review is presented of the commercially available glandless drives in which rotary motion is induced in a driven member by the rotating magnetic fields of the driving member.

The description is given of a commercial glandless drive in which permenent magnets are employed to generate the rotating field. The results of a series of experiments designed to determine the best practical field distribution are given.

The probable mechanism of the flux employment is discussed.

It is concluded that the commercial drive described does not use to the full the permanent magnet field available. An arrangement of the permanent magnets to use more efficiently the flux available is suggested.

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Permanent Magnet Couplings for Glandless Rotary Drives

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1. In recent times two forms of rotary glandless drive have become available commercially. These drives are usually associated with pumps but can also be adopted for driving stirrers in closed vessels. The common feature of the tow types is the use of a rotating magnetic field to induce rotation in the driven member of the coupling, this member being completely isolated from the driving member by the wall of the pump or vessel. They differ fundamentally in the method by which the rotating field is produced, polyphase alternating currents in conjunction with a suitably wound stator, being used in one case, whilst in the other a system of permanent magnets is employed, mounted on bearings and driven by a prime mover.

When alternating currents are used, the drive is in the form of a squirrel cage motor with its airgap increased to enable a non-magnetic diaphragm to be inserted between the stator and rotor. The rotor with its bearings is completely separated from the stator by the diaphragm, which becomes part of the pump casing or vessel wall. Due to the necessarily large airgap, such a motor has a lower efficiency than a standard machine and the consequent losses appear as heat which has to be removed. The enclosure of the rotor upsets the normal motor ventilation system and the removal of the heat must be achieved in other ways. When such a drive is used in a pump the liquor being handled is usually used as the coolant. It is allowed to circulate round the rotor and extracts the heat from the stator through the diaphragm. The Sigmund Thermo Pack circulator for central heating systems is a typical example of the construction employed.

The use of permanent magnets enables a more efficient prime mover to be used and the cooling of the coupling is unlikely to require special attention; against these advantages must be considered the provision of a bearing system for the housing of the permanent magnets which may be in the form of either a disc or drum. The magnets are mounted so that their poles face the diaphragm and the field so formed is used to react with a rotor within the pump or vessel. This rotor can be constructed so as to employ a number of different reactions with the rotated field to induce rotation in itself; viz eddy currents, magnetic hysteresis or attraction and repulsion. For the large airgaps necessary for the drives under consideration the last mentioned reaction is the most satisfactory for the transmission of large torques and it is to its use that attention is drawn.

2. The component parts of a stirrer drive incorporating a permanent magnet coupling are shown in Figure I. This drive was manufactured by Hydraulic and Mechanical Developments Ltd. of 116 Victoria Street, London, and the coupling is a Howard Permanent Magnet Coupling, to Patent No. 670682, having a pull-out torque of 10 lb. ft. In this coupling permanent magnets are housed in the outer driving member and the inner driven member. The magnets are of 'horse-shoe' form and are arranged in the two parts of the coupling to form a series of magnetic circuits as shewn in Figure II. When the coupling is loaded, one ring of magnets is displaced relative to the other and the two parts of the coupling run at the same speed with a constant relative displacement. If the coupling is overloaded, the driven member comes to rest with no torque being exerted on it.

It is claimed by the manufacturers that it is the tangential component of the attraction forces between the unlike poles of the magnets in the two halves of the coupling that is the source of the torque transfer. Critical examination of Figure II suggests that this is not the sole contributor to the torque transfer capacity. The figure shows that when the outer row of magnets is moved relative to the inner row the unlike poles uncover one another and at the same time like poles are made to approach one another. From this it is seen that for each pair of magnets 4 poles contribute attractive effort and 2 poles repulsive effort. The torque capacity can thus be said to be the combined effect of attraction and repulsion. Examination of the actual coupling suggested that the magnet arrangement could be improved to utilise this combined effect if the Push-Pull theory is tenable. In the coupling shewn in Figure I the width of the poles was equal to the interpolar gap for the individual magnets which were set in the coupling so that the space between them was equal to their own width over the poles. To obtain the full repulsion effort from all poles it appears essential that the sequential poles, in each half coupling, should be equally spaced from each other.

3. The validity of the 'Push-Pull' theory depends on proof that the repulsion effect between the approaching like poles contributes a substantial component to the torque capacity of the coupling. In order to test the theory, a series of experiments was designed to determine the order of the contribution that could be expected from the repulsive effort.

It was anticipated that the magnet proportions would have an influence on the results and to obtain information on this point the first experiments employed three standard commercial magnets of different shapes, shewn in Figure III. Magnet (a) was chosen for its square pole faces and its short interpolar gap as compared with that of magnet (c). The third magnet (b) was chosen for the greater length of pole face normal to the direction of magnetisation with a small interpolar gap and narrow poles.

The rig, shewn in Figure IV, was made to carry a pair of magnets, so that they could be mounted to form an element of a coupling. One magnet was held stationary while the other, mounted on a balanced arm on a ballrace pivot, could be moved relative to it. Provision was also made for the air gap between the poles of the two magnets to be varied between 2 and 16 mm. The magnets could be mounted so that they could be displaced relative to each other either in the plane containing the direction of magnetism or at right angles to it. Figure V indicates that the first direction of relative movement is in the plane of the paper and will be resisted by the attraction of two pairs of unlike poles and the repulsion of one pair of like poles. The second direction of relative motion takes place at right-angles to the plane of the paper and will be resisted by the attraction of two pairs of unlike poles only. To measure the maximum resistance to relative motion, the balanced arm of the rig was loaded in increments and the greatest load supported without the arm dropping was recorded. All the magnets were tested for both modes of relative motion and over the range of airgaps possible with

the rig. The results for the magnets, plotted against the airgap, are shewn in Figures VI, VII and VIII, from which it will be seen that the greatest resistance to relative motion is produced when both attraction and repulsion forces are brought into play in all cases. These results are summarized in Table I where the ratio:-

$$\frac{\text{Maximum Resistance to relative motion in direction of Magnetism}}{\text{Maximum Resistance to relative motion normal to direction of Magnetism}}$$

is given for two values of airgap for the three magnets a, b and c.

Table I

Magnet	Ratio at Airgap	
	13 mm.	2 mm.
a	2.2	1.34
b	2.23	2.22
c	1.81	1.34

It is seen that the repulsive effort is a considerable factor in producing resistance to the relative displacement in a coupling of the Howard design, and consequently its capacity for torque transmission. The results also reveal differences in the repulsive effort produced by the magnets used in the tests. Magnets (a) and (c) show that the repulsive effort becomes more important as the airgap increases and it is evident that the shorter interpolar gap of magnet (a) may have some influence in its favour at the longer airgap. Magnet (b) shows a consistency over the whole range of airgap dimensions which may be attributed to the wider front of action normal to the direction of the relative motion provided by the longer poles.

If the ratio in Table I for magnet (b) is considered it is seen that the component values for the attraction and repulsion effects can be deduced. Let the attraction effort be unity then the repulsion effort is the difference between the ratio in the table and unity. The tests having used the same pair of magnets the results are not influenced by any variation in the flux linkages between them. Hence for the magnet (b) pair 4 poles contribute 1 unit of attractive force and 2 poles 1.2 units of repulsive force. From this it is seen that if all the poles in the Howard coupling can be made to produce to the full both attraction and repulsion effort the torque available can be increased with the same number of magnets employed. Using the values deduced for magnet (b) the increase in torque would be 1.2 units in 2.2 units or 54.5%.

4. The foregoing arguments have been based on the evidence of a single magnetic circuit and do not take into account any interaction that may take place between the unit circuits when built into a coupling. An experimental check was carried out using the magnets to Figure III (b) in a series of disc type couplings with constant airgap and different magnet arrangements. These magnet arrangements are shewn diagrammatically in Figure IX (a)-(d). Couplings of $2\frac{1}{2}$ and 5 inch pitch circle diameter at the magnet centres were built. On the 5 inch pitch circle all the magnet arrangements could be built, with 10 magnets in arrangements to Figure IX (a) and (b) and 20 magnets in the other two, these figures being for each half coupling. In the $2\frac{1}{2}$ inch pitch circle couplings the number of magnets was 5 and 10 respectively. The coupling arrangement to Figure IX (b) could not be used with 5 magnets. With one

half coupling fixed the other was loaded tangentially and the maximum load supported without the coupling slipping was measured. The experimental figures, which are given in Appendix I, confirm that for both diameter couplings the magnet arrangement to Figure IX (d) will support more than twice the maximum load supported by magnet arrangement to Figure IX (a). The couplings are compared by the ratio:-

$$\frac{\text{Maximum Load supported by 2 x magnets to Figure IX (d)}}{\text{Maximum Load supported by x magnets to Figure IX (a)}}$$

Table II

Pitch Circle diameter of Magnets in inches	Ratio
$2\frac{1}{2}$	2.49
5	2.69

From these ratios it is seen that the magnet arrangement to Figure IX (d) produces $24\frac{1}{2}$ and $34\frac{1}{2}$% increase in the effort exerted by each magnet pair in the respective couplings. That this increase is not as great as the earlier work suggested, indicates that the width of the combined poles being greater than the interpolar gap of the individual magnets did not allow the development of the maximum effort.

The load supported figures for the other couplings show that whilst the magnet arrangements Figure IX (a) and (b) for a 5 inch P.C.D. coupling produce the same effort, the arrangement to Figure IX (c) would not support the load that half the number of magnets to arrangements Figure IX (a) and (b) will support. This fall in load capacity can only be due to the cross linkage of flux between the adjacent unlike poles in each half coupling at the expense of the linkage across the airgap. From this it is to be assumed that if the magnets in Figure IX (a) are pitched so that the gap between the adjacent magnets is equal to the interpolar gap of the individual magnets considerable cross linkage will occur to the detriment of the torque capacity of the coupling.

The above results show that the magnet arrangement to Figure IX (d) is the most efficient and that improved results could be expected if magnets having an interpolar gap of twice the width of their poles were used.

5. All the previous results have been based on couplings with a single row of magnets. The initial experiments with individual magnets indicated that a magnet with poles whose length in the direction normal to that of relative displacement is greater than their width, may be the more efficient for use in couplings. A comparison is therefore necessary between the load capacity of couplings employing the same magnets in arrangement to Figure IX (d) and a double row arrangement to Figure IX (a). For tests of this order a drum type coupling is superior to the disc type and for this reason a drum type coupling was used in the last series of tests. The details of the experimental coupling are shewn in Figure X. The construction of the coupling enabled up to 24 magnets per half coupling to be used in 1 to 3 rows of 8 or 1 to 6 rows of 4. This enabled direct comparison to be made between the Howard arrangement and the proposed arrangement using the same magnets with 8, 16 and 24 per half coupling. To investigate the influence of the pole proportions two sets of 48 magnets were obtained, the first to Figure XI A with an interpolar gap twice the width of the poles and the other to Figure XI B with the interpolar gap equal to the pole width.

It will be seen from Figure X that the inner magnet drum is fixed to the angle supports and the outer magnet drum is mounted on ballraces which are housed on the shaft extending from the inner half of the coupling. The load was applied by weights on a scale pan supported by a cord anchored to and wrapped round the major diameter of the outer magnet housing. A scale fixed to the support angle and a pointer mounted on the outer magnet housing were the means of measuring the relative displacement of the two parts of the coupling. The range of couplings built for the tests are identified in the following:-

Couplings IA. with magnets A Figure XI assembled to Figure IX (a) giving couplings with from 1 to 6 rows of 4 magnets per half coupling.

Couplings IIA. with magnets A Figure XI assembled to Figure IX (d) giving couplings with 1 to 3 rows of 8 magnets per half coupling.

Couplings IB. with magnets B Figure XI assembled to Figure IX (a) giving couplings with from 1 to 6 rows of 4 magnets per half coupling.

Couplings IIB. with magnets B Figure XI assembled to Figure IX (d) giving couplings with from 1 to 3 rows of 8 magnets per half coupling.

A coupling is fully identified by a numerical suffix indicating the number of rows of magnets in it; thus a 2 row assembly of Coupling IIA will be referred to as Coupling IIA.2.

The maximum supported load without slip was measured for all the 18 couplings with their relative angular deflection as the loading took place. Figure XII shews the maximum load supported by each series of couplings plotted against the total number of magnets in the coupling. In Figure XIII the load is plotted against angular displacement for the couplings IA.6, IIA.3, IB.6 and IIB.3. The maximum load figures for each series of couplings will be seen from Figure XII to substantially follow a straight line law and the mean line has been drawn for each series. The ratios quoted in Table III have been derived from the mean line for each coupling. The experimental figures are given in full in Appendix II. It is clear from Figure XII that the series IIA and IIB couplings can support greater loads than their series IA and IB counterparts on the bases of the number of magnets employed. The graphs do not however show that the series IIA and IIB couplings have half the number of rows as their respective series I counterparts with the same number of magnets. The couplings can therefore be compared on the basis of the number of magnets or on the number of rows. Table III shows the comparisons in the form of Ratios which are derived from:-

$$\frac{\text{Maximum Load supported by Coupling IIA. or IIB.}}{\text{Maximum Load supported by Coupling IA. or IB.}}$$

the ratios being obtained on the basis of the same number of magnets in each coupling and on the number of rows for each magnet.

Table III

Magnet A Fig. XI				Magnet B Fig. XI			
No. of Rows	Ratio	No. of Magnets	Ratio	No. of Rows	Ratio	No. of Magnets	Ratio
1	3.13	16	1.135	1	2.72	16	1.07
2	2.84	32	1.245	2	2.45	32	1.105
3	2.79	48	1.28	3	2.39	48	1.11

It is seen that the series II couplings support a greater load than their series I counterparts both on the basis of the number of magnets and of rows. Examining the ratios on a row basis it is seen that the ratio decreases as the number of rows increases. This can only be due to the increase in efficiency in the use of the available flux by the series I couplings as the number of rows increases. At the same time the series II couplings increase in their efficiency in the use of the flux as is shewn by the increase in the ratio on the basis of the number of magnets employed. From the load graphs of Figure XII can be deduced the limiting values of these ratios and it is found that on the number of rows basis they are never less than 2.66 for magnet A and 2.24 for magnet B. Similarly on the basis of the number of magnets the ratios will never exceed 1.3 for magnet A and 1.12 for magnet B. The practical value of the above results is that the series IIA couplings are only half the length of their series IA counterparts and obtain an increase of not less than 13% in the load supporting ability of each magnet pair. It is of interest to note, at this point, that the coupling IIA.1. supports 56.5% more load per magnet pair than the coupling IA.1. which is greater than the 54.5 % predicted in section 2 above.

6. The results given in the previous section can only be interpreted to the full if the relative displacement of the magnetic poles in each half coupling to the other is known. Figure XIII shews the load against displacement curves for couplings IA.6, IIA.3, IB.6 and IIB.3, from these curves and the physical dimensions of the magnets it is possible to determine the relative positions of the two sets of poles in the coupling for any load. It is however the position of maximum load support that will be studied in detail.

The dimensions of magnet A Figure XI are such that each pole subtends an arc of $11\frac{1}{4}^{\circ}$ and the interpolar gap one of $22\frac{1}{2}^{\circ}$, the whole magnet subtending 45° of arc. For magnet B Figure XI the poles subtend an arc of 15° each as does the interpolar gap and the whole magnet an arc of 45°. Using these magnet dimensions and the measured angular displacement at maximum load for the four couplings the position of the poles can be deduced as below:-

<u>Coupling IA.6</u> the relative displacement was 11.5° which indicates that the opposing unlike poles in the two half couplings have just uncovered one another thus:-

```
|N - - S|        |N - - S|        |N - - S|                  Fixed.
   |S - - N|        |S - - N|        |S - - N|   ------->    Direction of
                                                             Displacement.
```

<u>Coupling IIA.3</u> the relative displacement was 24° thus indicating that the composite poles of each half coupling were facing the interpolar gaps of the magnets in the opposite half:-

```
|N - - S|S - - N|N - - S|S - - N|N - - S|S - - N|            Fixed.
 - S|S - - N|N - - S|S - - N|N - - S|S - - N|N -   --->      Direction of
                                                             Displacement
```

Coupling IB.6 the relative displacement was 15° and can be shewn thus:-

```
|N - S|      |N - S|      |N - S|      |N - S|            Fixed.
  |S - N|      |S - N|      |S - N|      |S - N| ---->    Direction of
                                                          Displacement.
```

Coupling IIB.3 in this coupling the relative displacement of 23° indicated that the composite poles in one half coupling had centred themselves within 1° with the interpolar gaps of the magnets in the other half coupling thus:-

```
|N - S|S - N|N - S|S - N|N - S|S - N|N - S|S - N|          Fixed.
- S|S - N|N - S|S - N|N - S|S - N|N - S|S - N|N -  ---->   Direction of
                                                           Displacement.
```

From the above it will be seen that the couplings IA.6, IIA.3 and IB.6 have in common the uncovering of unlike poles at the position of maximum load support, also couplings IIA.3 and IB.6 have the same relative position of like poles. Coupling IIB.3 has overlapping of both unlike and like poles which suggests that the full attractive effort is not being developed due to the overlapping of the unlike poles. The overlapping of the like poles may also mean that the full repulsive effort is not being developed. From the other couplings it can be assumed that the full attractive effort is produced just as the unlike poles uncover one another. That this position of unlike poles does not occur in Coupling IIB.3 can only be attributed to the conditions for load support becoming unfavourable as the like poles begin to cover one another. To check on the relative pole positions for a coupling in which repulsion could be expected to be the major contributor to the load support, the coupling IB.6 was modified to give the following pole conditions in the unladen condition:-

```
|N - S|      |N - S|      |N - S|      |N - S|
     |N - S|      |N - S|      |N - S|      |N - S|
```

The coupling on being loaded to its maximum capacity had a deflection of 28 to 30° which was indicative of a pole relationship of:-

```
  |N - S|      |N - S|      |N - S|      |N - S|           Fixed.
|N - S|      |N - S|      |N - S|      |N - S| ---->       Direction of
                                                           Displacement.
```

This pole relationship is seen to be the same as that for the unmodified coupling IB.6. The load supported by the modified IB.6 was found to be 1475 grammes against the 1882 grammes for the original IB.6. The same magnets having been used in both couplings it is possible to assess the contribution of the two components i.e. Attraction and Repulsion - since in IB.6 (unmodified)

Σ (Attraction effort of 2 poles + Repulsion effort of 1 pole for each magnet) = 1882 g.

and in IB.6 (modified)

Σ (Attraction effort of 1 pole + Repulsion effort of 2 poles for each magnet) = 1475 g.

From this it is found that in Coupling IB.6 the attraction effort is 1526 grammes and the repulsion effort 356 grammes and for the modified IB.6 the figures are 763 and 712 grammes respectively. Using these values for the two components of the load supporting capacity it will be seen that if the interpolar gaps of the individual magnets in Coupling IIB.3 could be opened up to twice their present dimensions the coupling should then produce a load support figure of:-

1526 grammes of attractive effort + 712 grammes of repulsive effort = 2238 grammes.

Using this result it is of interest to determine the ratios of load supported to coupling IIB.3 on a row basis and to coupling IB.6 on the basis of the number of magnets employed. These ratios are:-

Ratio of loads supported on the basis of the number of magnets

$$= \frac{\text{IIB.3 modified}}{\text{IB.6}} = \frac{2283}{1883} = 1.21$$

Ratio of loads supported on the basis of the number of rows

$$= \frac{\text{IIB.3 modified}}{\text{IB.3}} = \frac{2283}{843} = 2.71$$

It is seen that these ratios approach those obtained for the corresponding IIA and IA couplings. They will not equal those ratios because the IB series couplings are more efficient than those of the IA series.

A check experiment was made using 16 of the type B magnets. In this experiment a IIB.1 coupling was assembled and the maximum load supported measured, this was 555 grammes. The 16 magnets were then modified by grinding the inner flanks of the pole pieces away until the interpolar gap was twice the width of the pole pieces, the magnets were then re-assembled into a single row coupling. The maximum load supported by this coupling was 673 grammes, thus demonstrating the superior load capacity of a coupling whose pole faces and interpolar gaps subtend equal angles.

7. Examination of the proportions of the attractive and repulsive efforts making up the torque capacity of the IB.6 coupling as deduced in section 6 above, reveals them to be totally different from those assumed in section 3. Expressing the proportions of the two components as a percentage of the maximum torque, coupling IB.6 has its torque composed of 68.2 % attractive and 31.8% repulsive effort, whereas the proportions assumed in section 3 are 29.3 % attractive and 70.7% repulsive effort. It becomes necessary, therefore, to reconsider the way in which the resistance to relative movement between the two parts of a coupling is developed.

In a coupling in the unladen condition the poles of one part of the coupling are in alignment with the unlike poles of the other and the flux linkages can be considered as acting in a direction substantially normal to the pole faces. On the application of a torque relative movement takes place between the two parts of the coupling and continues until the flux linkages produce a balancing torque. The way in which this balancing force is produced will be considered in the first place for two opposed unlike poles, the effects of the fields of adjacent poles being neglected.

The magnetic material employed is not in a state of magnetic saturation and the flux linkages will endeavour to retain the shortest path across the air gap (i.e. they will tend to retain a direction of action substantially normal to the pole faces). It can be assumed that for a small relative displacement of the opposing pole faces, the linkages will tend to concentrate in the area of the pole faces that remain opposed to one another. This increase in the flux density will be accompanied by an increase in the repulsion between the individual lines of linkage and it is this repulsion effort that produces the balancing force against the load causing the relative displacement. As the applied torque and therefore the relative displacement increases the flux density increases in the diminishing area of the pole faces opposed to one another, this action will continue until the flux density reaches an optimum value, producing increasing repulsion between the individual lines of linkage. The optimum value of the flux density is dependent upon

the characteristics of the magnet material and the length of the air gap normal to the pole faces, the final flux density obtainable decreasing as the air gap lengthens. In step with this flux concentration there will develop linkages from the exposed faces of the uncovering poles, whose general line of action will be at an angle to the pole faces; these will be attractive in action and have a component force acting in a direction parallel with the pole faces, which resists the relative displacement. As the relative movement of the poles increases beyond the point at which the maximum value of flux concentration is achieved, increasing numbers of linkages of the attractive type will be formed adding their component force to resist the movement because less linkages will be able to maintain their path normal to the pole faces. Nevertheless even at the point of maximum displacement, when the poles have completely uncovered one another, the resisting force will still have a component derived from the mutual repulsion between the lines of linkage which will seek to concentrate across the shortest air path. Thus for two unlike poles no clear division can be made between the attractive and repulsive components of the force resisting the relative displacement, since in the initial stages of displacement the resistance is purely repulsive and changes gradually to a combination of repulsive and attractive effort as the displacement increases, the attractive effort becoming more important as the point of maximum displacement is reached.

Consideration must now be given to the effect of the fields of adjacent poles on the two poles discussed above. Referring to the pole displacement diagram for the coupling IIA.3 in section 6, it will be seen that as a displaced pole uncovers its opposing unlike pole it is itself approaching a like pole, at the same time it is being followed up by an unlike pole. As the like poles approach one another mutual repulsive forces will be brought into play and their intensity will increase with the relative displacement. The component of this mutual repulsion which acts in a direction parallel with the pole faces will assist in resisting the relative displacement. The repulsion between the like poles will also have the effect of assisting the flux linkages between the uncovering unlike poles to concentrate in the opposed faces of those poles and at the same time the attractive linkages will be forced into shorter paths thus increasing their contribution to the resistance to relative motion. The effect of the approaching like poles is, therefore to produce both repulsive and attractive effort and no clear division can be made between them as assumed in sections 3 and 6.

8. From the proceeding section it is seen that the torque capacity of a coupling is best thought of as the resistance of the magnetic field to distortion. In resisting the relative displacement of one part of the coupling to the other the magnetic field has to do work, this work can be calculated from the load-displacement curve for the coupling. For the experimental couplings the work done by each can be calculated from the curves shewn in Figure XIII. The work done being given by:-

$$\left(\text{Area under Curve} \times \frac{6.75\ \pi}{180}\right) \text{ Centimetre-grammes.}$$

Table IV shews the values calculated for the magnets A and B to Figure XI when used in the two types of magnet arrangements.

Table IV

Magnet	Coupling	Number of Magnets	Volume of Magnets (cc.)	Maximum Relative displacement Degrees	Work done by Coupling (cm. g.)	Work done per cc. of Magnet (cm. g.)
A Fig. XI	IA.6	48	144	11.5	990	6.9
"	IIA.3	48	144	24	2656	18.4
B Fig. XI	IB.6	48	192	15	2023	10.6
"	IIB.3	48	192	23	3665	19.1

It is seen from the Table that the magnets A do 2.68 times the work when used in the IIA.3 coupling than they do in the IA.6 coupling, the corresponding figure for the magnet B being 1.81. The magnet arrangement used in the IIA and IIB couplings therefore extracts more work out of the magnets than the magnet arrangement used in the IA and IB couplings. If th. coupling IIA.3 is studied in detail it is seen that the individual pole faces and the interpolar gaps subtend equal angles namely $22\frac{1}{2}^{o}$ approx. The maximum force resisting relative motion is developed at a displacement of 24^{o} approx., it may be taken that this angle is equal to the angle subtended by the pole face for practical purposes. Providing that these two values are always equal it appears probable that the amount of work obtained from each cubic centimetre of magnet employed will be the same for any value of the angle subtended by the pole faces. Thus if the same volume of magnetic material as employed in the coupling IIA.3 is disposed so that there are 16 consequential poles whose faces subtend an angle of $11\frac{1}{4}^{o}$ with interpolar gaps subtending the same angle, then the maximum tangential force will be developed with a relative displacement of $11\frac{1}{4}^{o}$ and the work done by the coupling will be the same as that done by the IIA.3 coupling. The displacement of the new coupling is only half that of the IIA.3 therefore the tangential force will approximately be doubled, the mean diameter and air gap being maintained constant. It appears, therefore, that by adjusting the number of poles (always an even number) the characteristics of a coupling can be varied whilst employing the same volume of magnetic material. The torque will increase as the number of poles increases and the relative movement decreases and vice-versa. The maximum number of poles which can be employed in a coupling of fixed diameter will be influenced by the air gap required between the opposing magnets, in general the greater the 'Throw' required from a magnet the greater the interpolar gap is required to be. Subject to experimental determination of the optimum relationship between the length of air gap and interpolar gap it is felt that the latter should not be less than the former.

In the design of a coupling the torque required and the permitted relative movement between the two parts of the coupling will be known: the problem is to determine the magnet dimensions and characteristics of the material to be employed. For magnetic follower drives for instruments, in which a bar magnet is used with a non-magnetised magnetic material follower The General Electric Company of America* use an approximate method for the initial determination of the size of the magnet required. In this method the energy content of the magnet material at its chosen working point on the BH curve is

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* R.J. Parker, Permanent Magnets in Drag Devices and Torque Transmitting Couplings General Electric Review, Vol. 50 No.9 September, 1949.

equated with the work to be done by the magnet in resisting relative movement between the two parts of the drive as calculated from the known requirements, the equation being solved for the volume of magnetic material required. Further experimental work on the type of couplings discussed in this paper should lead to the determination of a similar method of estimating the volume of magnets required and for convenience the establishment of an equation of the form

$$T = K \frac{Em\,Vm}{\theta}$$

where T = Torque required at mean diameter of air gap

Em = Energy content of unit volume of magnet material

Vm = Volume of magnet material

θ = Angle of relative displacement in Radians

K = Constant (to be experimentally determined and will be influenced by air gap length, and axial length of coupling)

is desirable.

9. The imposition of a diaphragm in the air gap between the magnets of the two parts of the coupling will introduce an increase in the torque demanded from the prime mover. This will arise from the eddy currents induced in the diaphragm by the revolving magnetic field. The losses for a coupling of the IA or IB series are compared with those of a IIA or IIB series in Appendix III. It is seen that the losses are substantially the same for the same magnets employed in either series of couplings. In designing the diaphragm the walls must be kept as thin as possible in order to keep to a minimum the effective air gap between the magnet poles in the two half couplings. The material chosen must be non-magnetic and have a high electrical resistance. Stainless steel of the 18/8/1 class in its fully softened condition is a suitable material, alternatively the fibre glass materials with synthetic resin bonders of the polyester type or silicone bonding, for higher temperatures, offer the advantages of non-magnetic and non-conducting characteristics.

10. The results of this investigation show that

(a) The Howard coupling does not utilize fully the magnetic flux available.

(b) To obtain the maximum utilization of the magnetic flux the magnetic poles in each half coupling must be arranged to form a sequence of poles N - S - N - S with the width of the pole faces equal to the width of the interpolar gaps. Further all poles must be linked within the body of each half coupling by magnetic material.

(c) The findings are applicable to both disc and drum type couplings.

(d) Further experimental work is required to establish the relationship between the number of poles and torque for couplings employing the same volume of magnetic material.

11. Finally the authors wish to state that the load figures quoted in this paper must not be taken as indicative of the true capabilities of the magnets used, nor should the performance of magnets A and B be compared, since for experimental expediency they were purchased in the magnetized condition and ground as required when assembled in the couplings. That they produced consistent results in their random use in building up the series of couplings is an indication of the stability of modern magnetic materials when subjected to no little abuse.

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APPENDIX I to P.T.P. 582

In order to confirm deductions regarding magnet spacing and the utilisation of both the attractive and the repulsive effects of the magnet poles, a series of tests were conducted using the apparatus shown in Fig. XIV.

This apparatus consisted basically of two similar discs of $5\frac{1}{2}$ in. diameter, one being fixed and the other being free to rotate around a plain bearing. Each disc was drilled to accommodate 20 Button type magnets (Fig. III b) or a 5 in. P.C.D. or 10 such magnets on a $2\frac{1}{2}$ in. P.C.D., the discs being separated by a spacer of such length as to maintain an air gap of $\frac{1}{4}$ in. between opposing magnet poles.

Various magnet arrangements were tried as in Figs. IX a - IX d, ranging from 5 magnets on the $2\frac{1}{2}$ in. P.C.D. to 20 magnets on the 5 in. P.C.D., the maximum supported load being found in each case by loading the scale pan attached to the free disc, until the coupling slipped.

The results of these tests are tabulated below:-

No. of magnets	P.C.D.	Magnet spacing	Pole disposition	Max. load (g.)
5	$2\frac{1}{2}$ in.	Equally spaced	Unlike poles adjacent (Fig. IX a)	70
10	$2\frac{1}{2}$ "	In contact	" " adjoining (Fig. IX c)	64.5
10	$2\frac{1}{2}$ "	" "	Like " " (Fig. IX d)	174.5
10	5 "	Equally spaced	Unlike " adjacent (Fig. IX a)	262.5
10	5 "	" "	Like " " (Fig. IX b)	264.5
20	5 "	In contact	Unlike " adjoining (Fig. IX c)	245.5
20	5 "	" "	Like " " (Fig. IX d)	707.5

APPENDIX II to P.T.P. 582

As a means of comparison between the Howard and the proposed arrangement when applied to a drum type coupling, an experimental coupling of this type was made as in Fig. X, in which the inner drum was fixed, while the outer drum was free to rotate around it on ball-races mounted on an extension to the inner drum. The design was such as to allow various magnet arrangements to be accommodated, from 1 to 3 rows of 8 magnets or from 1 to 6 rows of 4 magnets in each drum.

Maximum torque values were obtained by loading a scale pan attached to a cord which was wrapped around and fixed to the outer circumference of the outer drum. A pointer attached to the outer drum registered with a fixed scale on the inner drum to indicate angular displacement as the load was increased to the point where the coupling slipped.

Tests were carried out on two sets of magnets, one set being to Fig. XIA, in which the interpolar gap is twice the pole face width, and the other set to Fig. XIB, having an interpolar gap equal to the pole face width.

The results of the tests are given below, and are shown graphically in Fig. XII.

Magnet XIA							
Coupling IA				Coupling IIA			
No. of rows	No. of magnets	Max. load (g.)	Displacement	No. of rows	No. of magnets	Max. load (g.)	Displacement
1	8	116	11.5°	1	16	363	24°
2	16	323	11.5°	2	32	916	24°
3	24	533	11.5°	3	48	1456	24°
4	32	703	11.5°				
5	40	946	11.5°				
6	48	1146	11.5°				

Magnet XIB							
Coupling IB				Coupling IIB			
No. of rows	No. of magnets	Max. load (g.)	Displacement	No. of rows	No. of magnets	Max. load (g.)	Displacement
1	8	223	15°	1	16	555	23°
2	16	513	15°	2	32	1362	23°
3	24	843	15°	3	48	2085	23°
4	32	1215	15°				
5	40	—	—				
6	48	1882	15°				

From these results it is possible to compare the two magnet arrangements in two different ways for each type of magnet (1) on the basis of the number of rows in each drum and (2) on the basis of the total number of magnets employed in the coupling, the ratio in each case being given by:-

$$\frac{\text{Max. load supported by Coupling IIA or IIB}}{\text{" \quad " \quad " \quad " Coupling IA or IB}}$$

Using figures read from the best mean line (Fig. XII for each series, the ratios obtained are:-

Magnet XIA							
On row basis				On magnet basis			
No. of rows	Coupling IA	Coupling IIA	Ratio IIA/IA	No. of magnets	Coupling IA	Coupling IIA	Ratio IIA/IA
1	116 grms.	363 grms.	3.13	16	320 grms.	363 grms.	1.135
2	320 "	910 "	2.84	32	730 "	910 "	1.245
3	525 "	1463 "	2.79	48	1145 "	1463 "	1.28

Magnet XIB							
On row basis				On magnet basis			
No. of rows	Coupling IB	Coupling IIB	Ratio IIB/IB	No. of magnets	Coupling IB	Coupling IIB	Ratio IIB/IB
1	215 grms.	585 grms.	2.72	16	545 grms.	585 grms.	1.07
2	545 "	1335 "	2.45	32	1210 "	1335 "	1.105
3	875 "	2088 "	2.39	48	1880 "	2088 "	1.11

APPENDIX III to P.T.P.582

Since the magnetic field rotates relatively to the wall of the shroud or diaphragm eddy currents are induced in it. The reaction of these eddy currents will resist the motion of the coupling. It is of interest to compare the losses in two couplings employing the same magnets as in Couplings IA and IIA.

To compare the losses the following assumptions must be made:-

(a) That the magnets cause the same total flux to pass through the coupling when in either coupling.

(b) The shrouds have the same mean diameter and wall thickness.

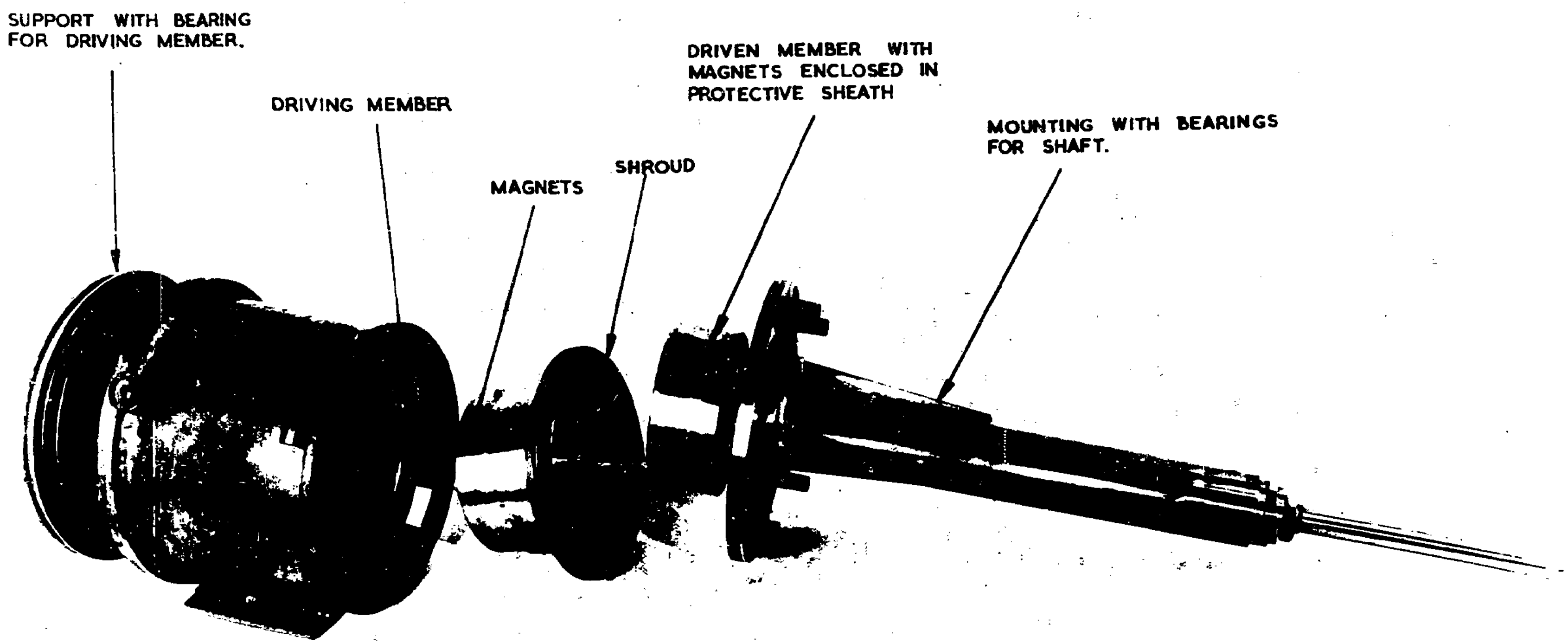
(c) The magnetic field rotates at the same angular velocity in both couplings.

The characteristics of the two couplings are :-

	Coupling IA	Coupling IIA
Field strength of Poles (gauss/cm.^{2})	H	H
Axial length of Poles (cm.)	L	$\frac{L}{2}$
Width of Poles (cm.)	W	$2W$
Mean Radius of Shroud (cm.)	R	R
Thickness of Shroud Wall (cm.)	t	t
Rotational Velocity of field Radians/sec.	w	w
Specific Resistance ohms/cm. cube	ρ	ρ
E.M.F. Produced under each Pole (volts)	$\frac{Rw}{W}.L.W.H.10^{-8}$ $R.w.L.H.10^{-8}$	$\frac{Rw}{2W}.\frac{L}{2}.2W.H.10^{-8}$ $\frac{1}{2}R.w.L.H.10^{-8}$
Assume length of Eddy Current Path under each Pole (cm.)	$2(L + a)$	$2(\frac{L}{2} + a)$
Resistance of Eddy Current Path (ohms.)	$\frac{2(L + a)\rho}{W.t.} 10^{-6}$	$\frac{(L + 2a)\rho}{2W.t.} 10^{-6}$

	Coupling IA	Coupling IIA
Eddy Current under each Pole (amps.)	$R.w.L.H.10^{-8} \times \frac{W.t.}{2(L+a)\rho} 10^{6}$	$\frac{1}{2} R.w.L.H.10^{-8} \times \frac{2W.t.}{(L+2a)\rho} 10^{6}$
	$5\left[\frac{R.w.L.H.W.t.}{(L+a)\rho} 10^{-3}\right]$	$10\left[\frac{R.w.L.H.W.t.}{(L+2a)\rho} 10^{-3}\right]$
Tangential force resisting rotation of coupling under each pole (dynes.)	$H. \frac{amps.}{10} L$ dynes.	$H. \frac{amps.}{10} \frac{L}{2}$ dynes.
	$5\left[\frac{R.w.L^2.H^2.W.t.}{(L+a)\rho} 10^{-4}\right]$	$5\left[\frac{R.w.L^2.H^2.W.t.}{(L+2a)\rho} 10^{-4}\right]$
(grammes)	$\frac{5}{981}\left[\frac{R.w.L^2.H^2.W.t.}{(L+a)\rho} 10^{-6}\right]$	$\frac{5}{981}\left[\frac{R.w.L^2.H^2.W.t}{(L+2a)\rho} 10^{-6}\right]$
or expressed in Watts per pole	$5\left[\frac{R^2.w^2.L^2.H^2.W.t.}{(L+a)\rho} 10^{-11}\right]$	$5\left[\frac{R^2.w^2.L^2.H^2.W.t.}{(L+2a)\rho} 10^{-11}\right]$

It is shewn that the expressions for the losses of the two arrangements differ only in the term expressing the length of the eddy current path. Since in practice the true length of the approximately rectangular path of the eddy currents will be indeterminate and further that the term 'a' will be small compared with the term L, then the losses for the two couplings can be considered equal.



P.T.P. 582

T.1352/1.

FIG. 1

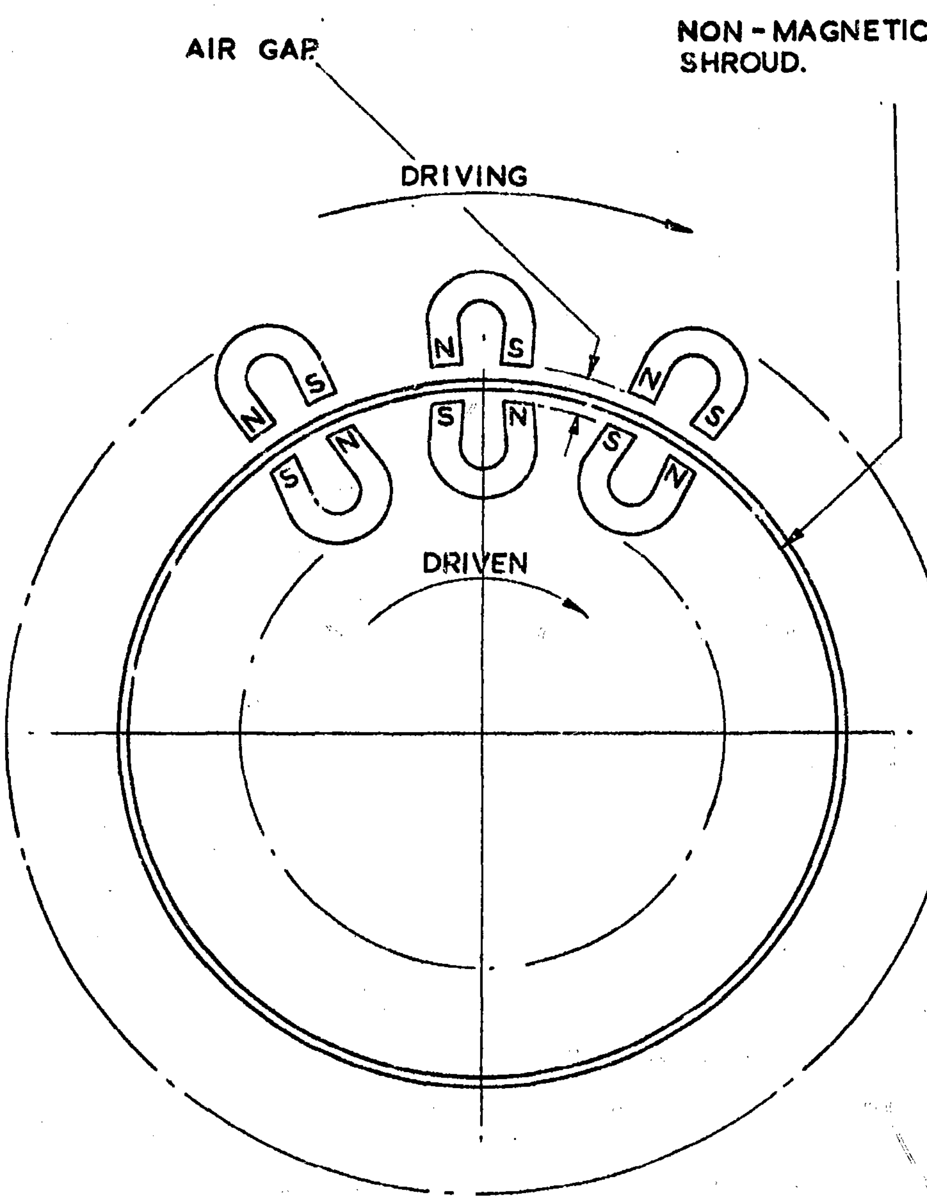
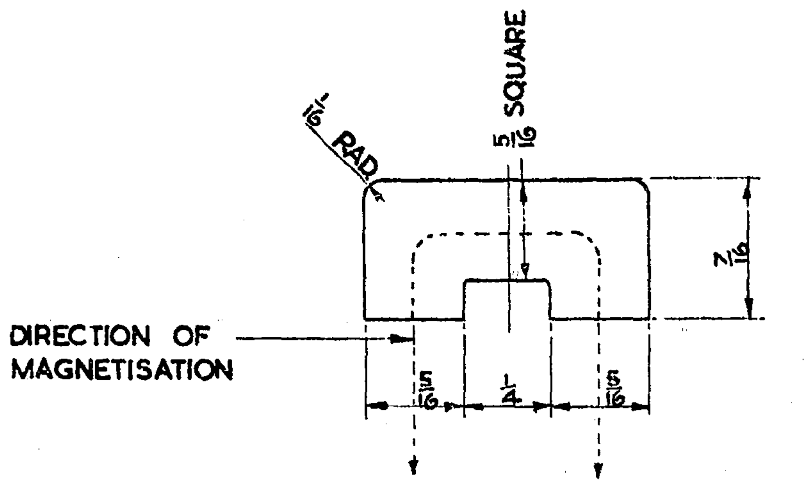
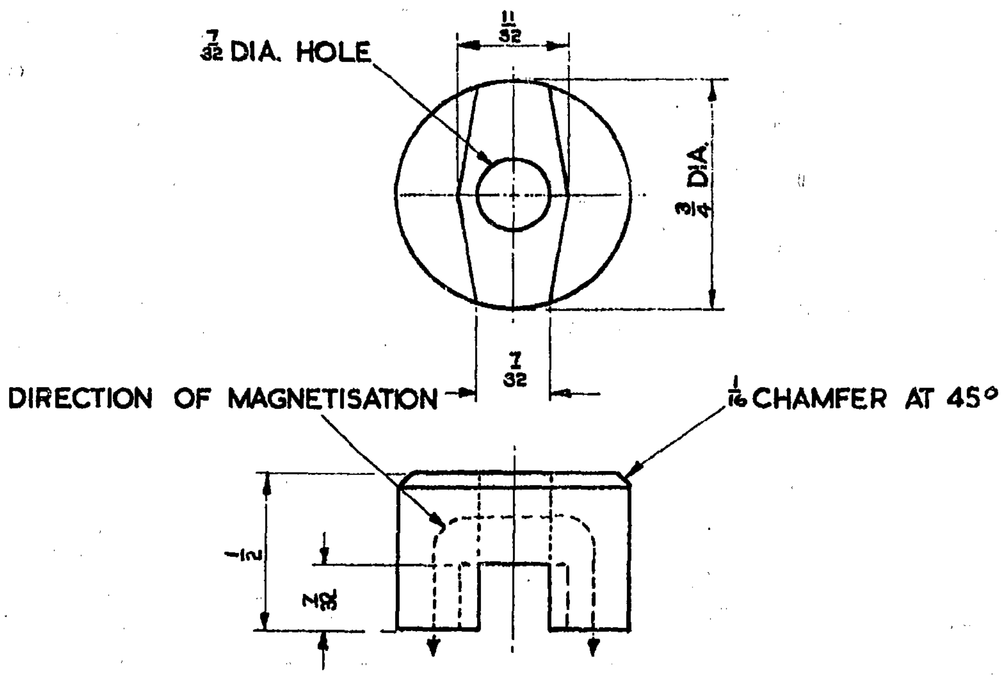


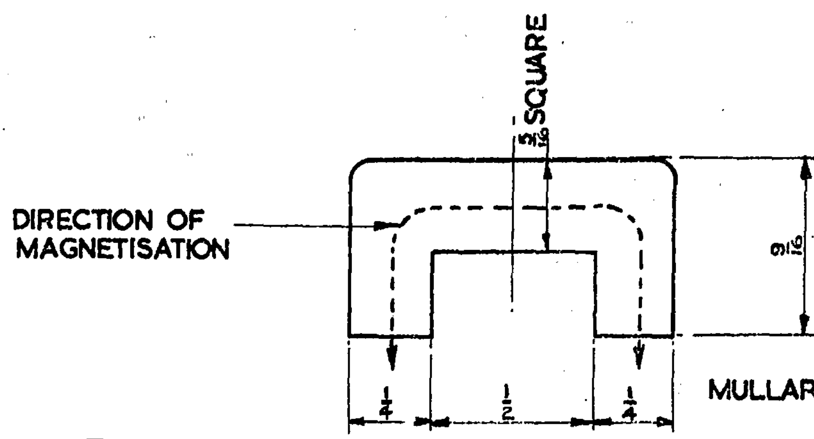
FIG. II MAGNET ARRANGEMENT OF HOWARD COUPLINGS.



(a) ECLIPSE MINOR MAGNET (ALNICO)



(b) ECLIPSE BUTTON MAGNET (ALNICO)

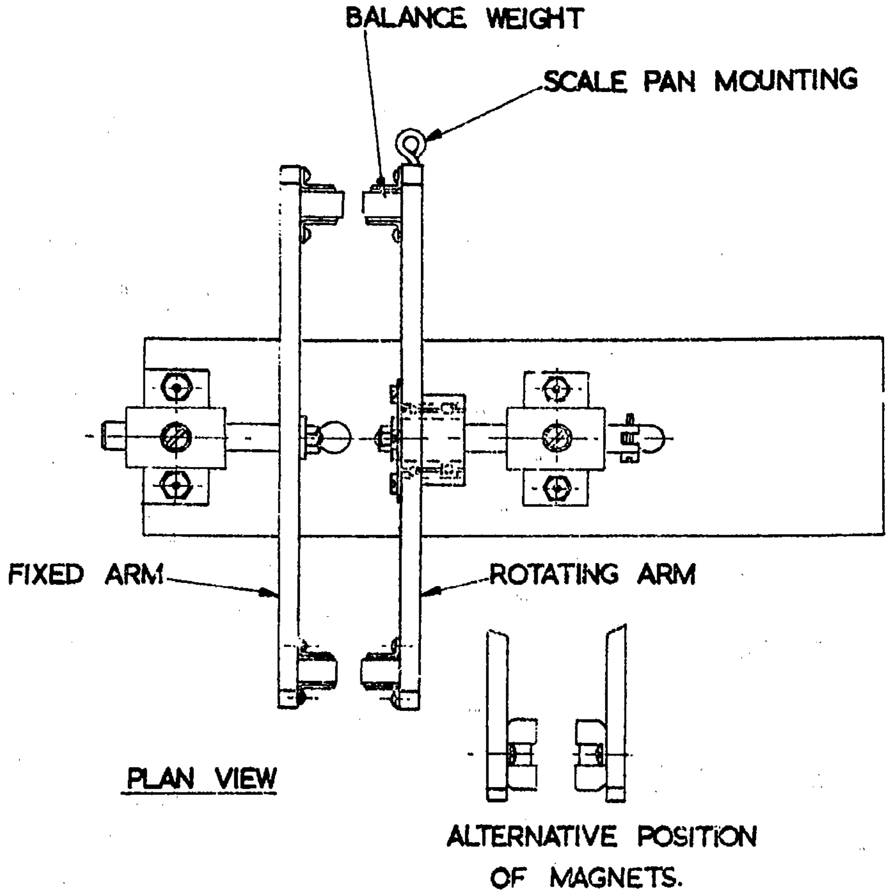


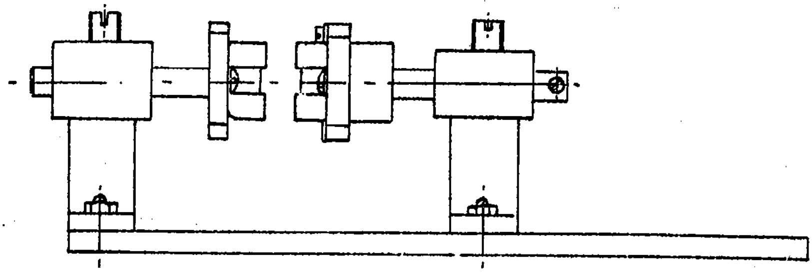
MULLARD TICONAL MAGNET

FIG. III

MAGNETS

TC.	M.E.S.	PORTON TECHNICAL PAPER Nº 582	PT 2589
CK.	C.D.E.E. PORTON.		DATE 13.12.55





SCALE 1/2

FIG. IV. TEST RIG FOR UNIT MAGNETIC CIRCUIT.

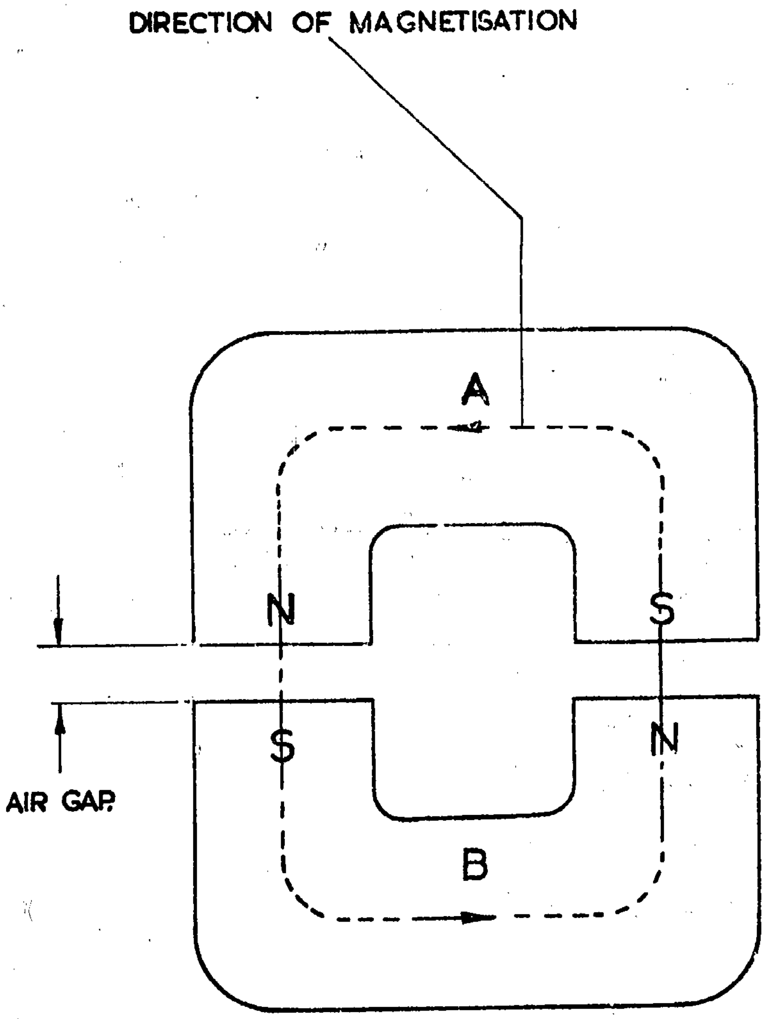


FIG. V

UNIT MAGNETIC CIRCUIT

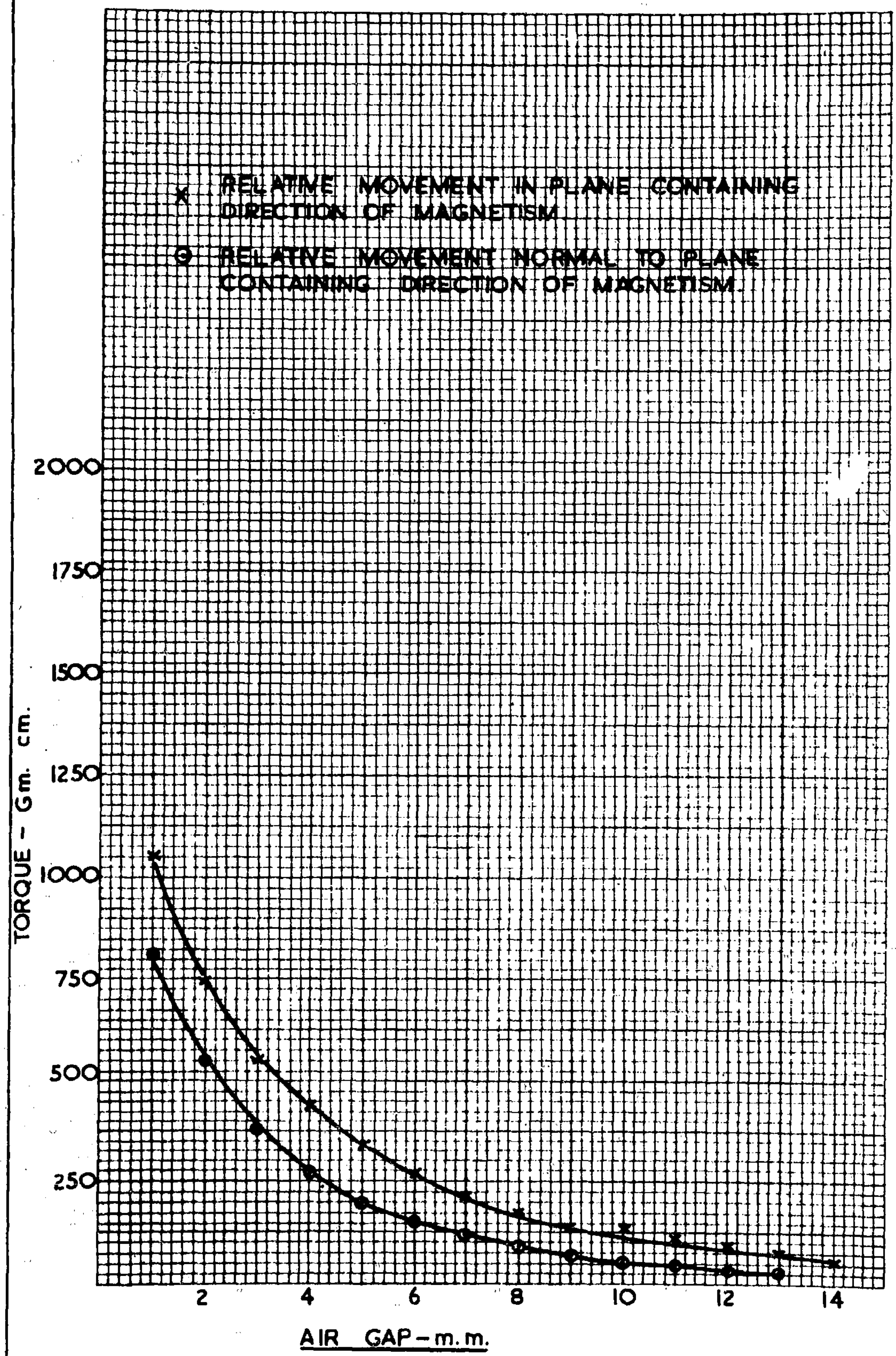


FIG. VI LOAD CURVES FOR MAGNET FIG. III (a)

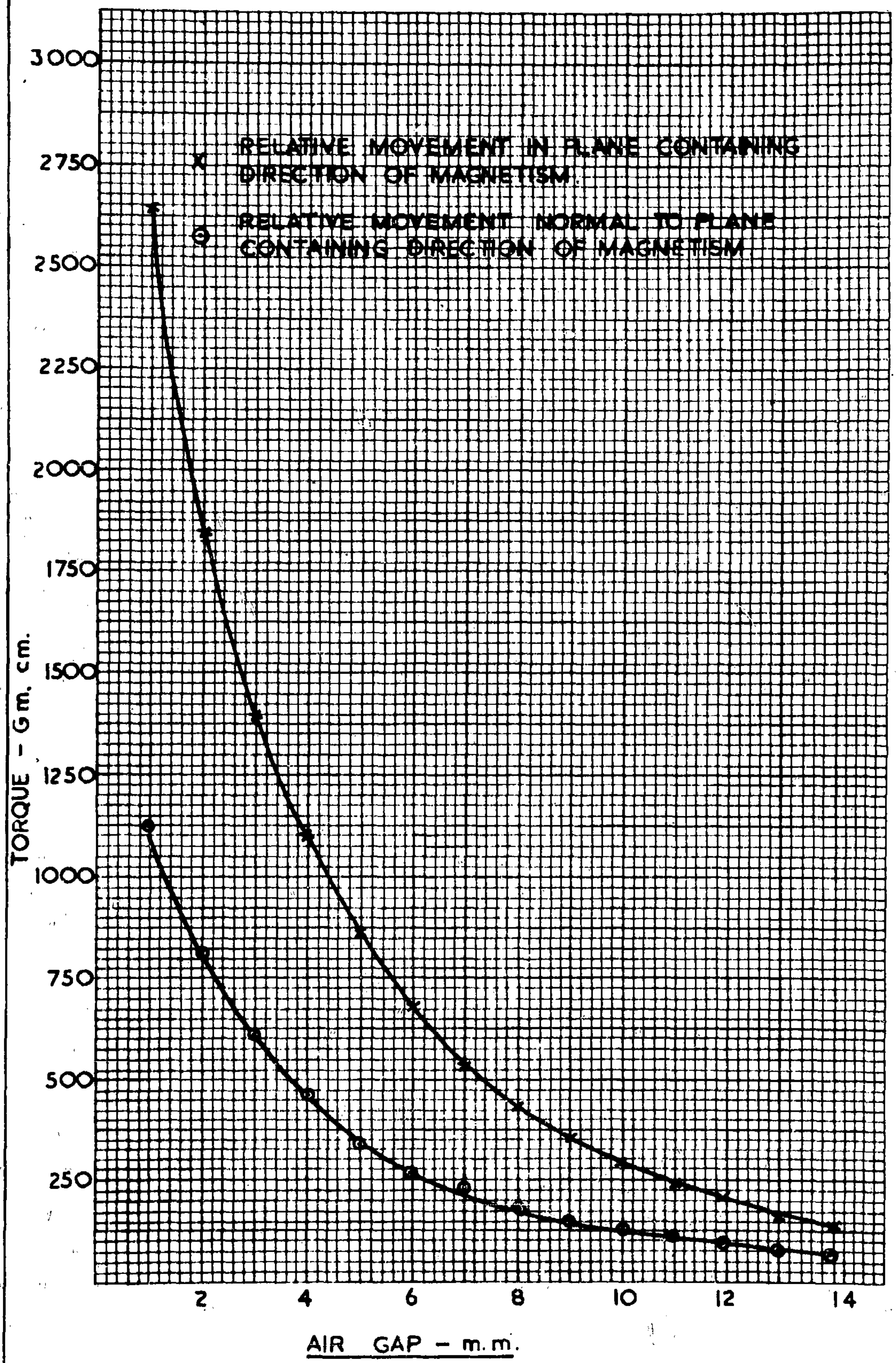


FIG. VII LOAD CURVES FOR MAGNET FIG. III (b)

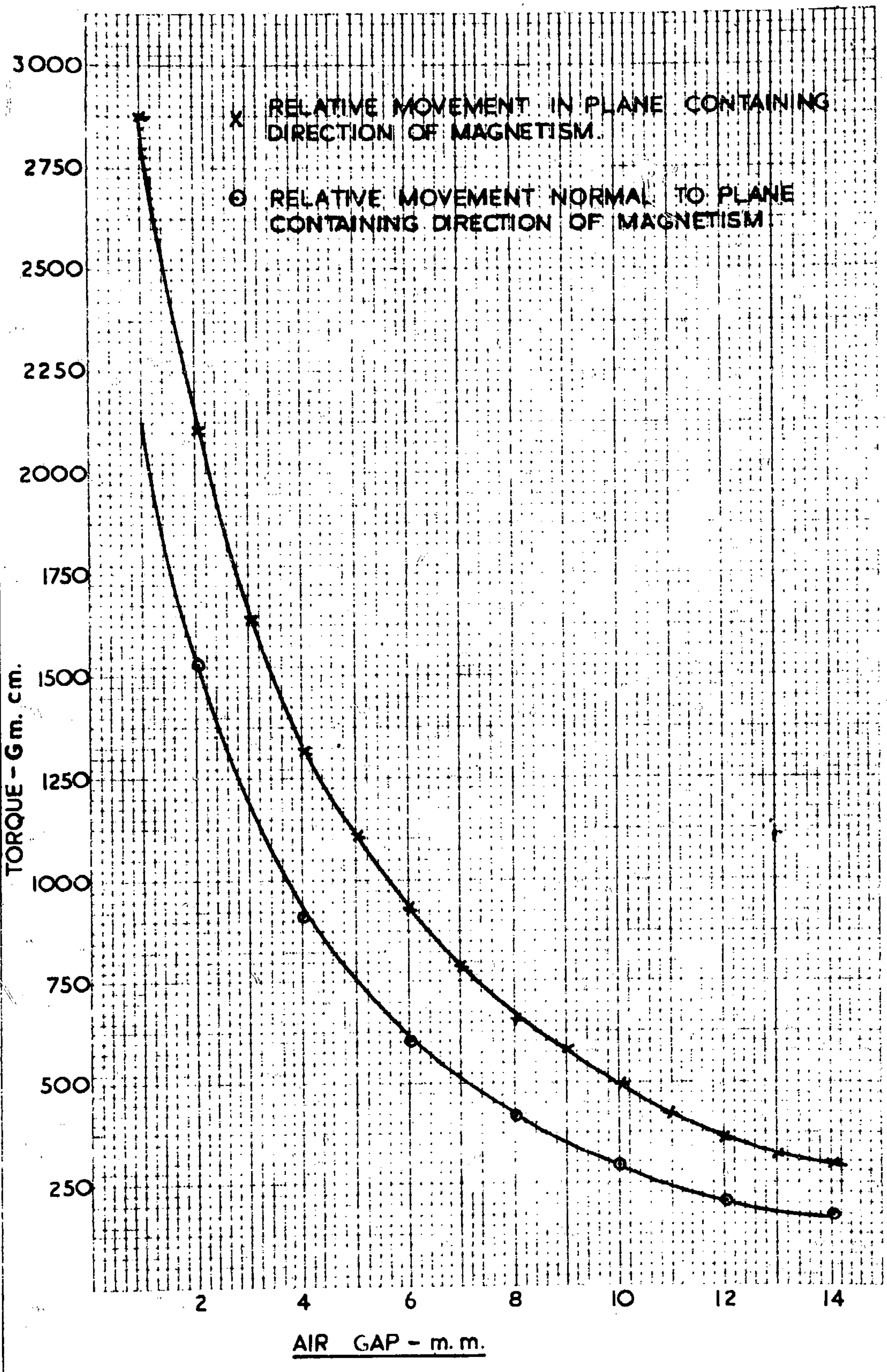


FIG. VIII LOAD CURVES FOR MAGNET FIG. III (c).

M.H.E.S. C.D.E.E. PORTON

PORTON TECHNICAL PAPER Nº 582

PT 2902
DATE 13-12-55

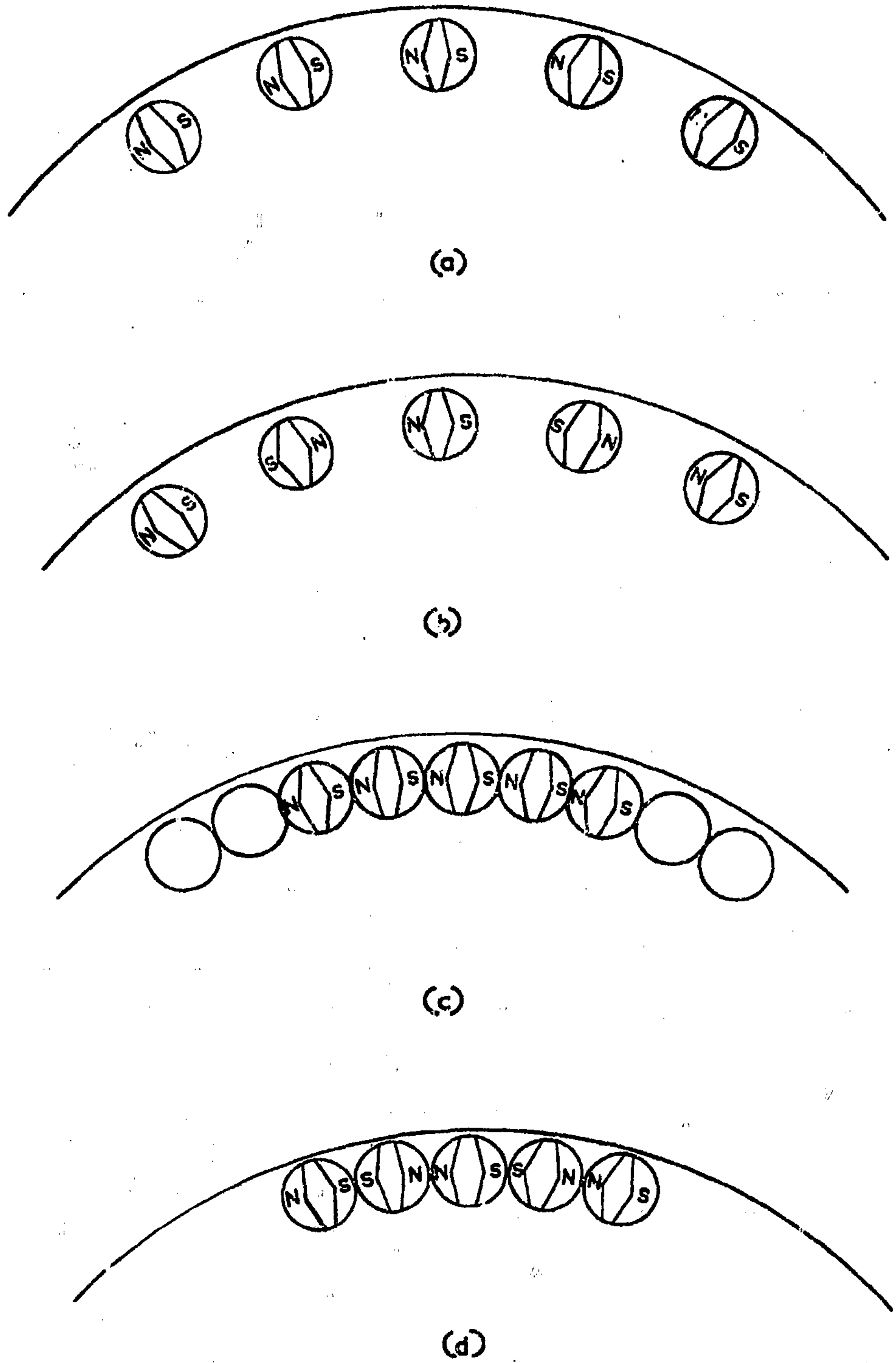


FIG IX MAGNET ARRANGEMENTS FOR EXPERIMENTAL COUPLING.

	H.E.S. C.D.E.E. PORTON.	PORTON TECHNICAL PAPER Nº 582	P 2588 DATE 13/12/5

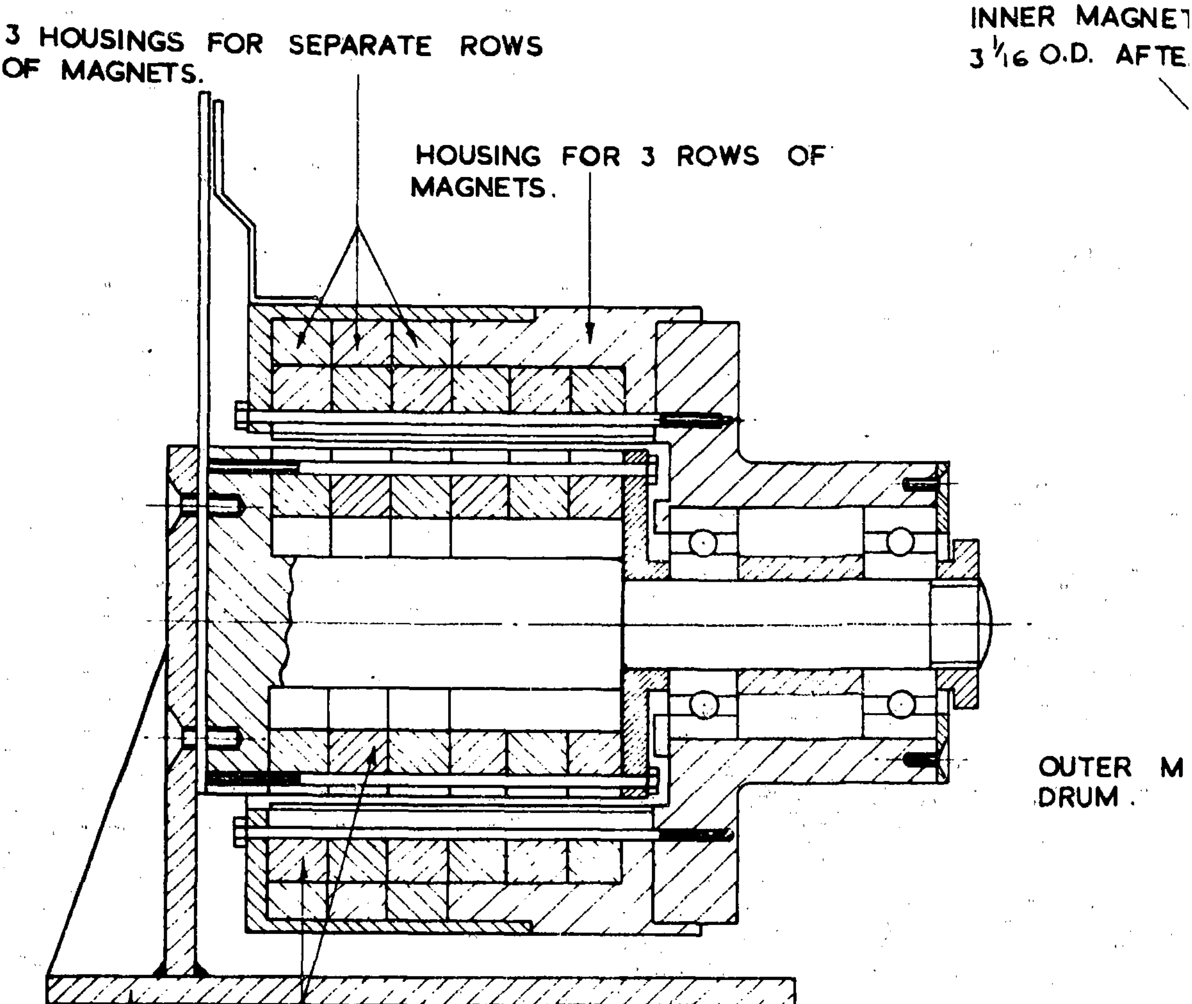
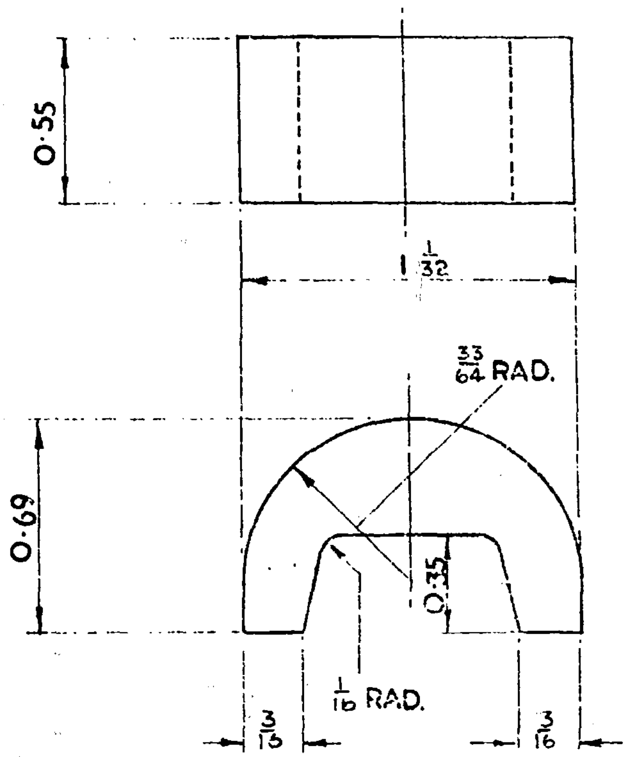
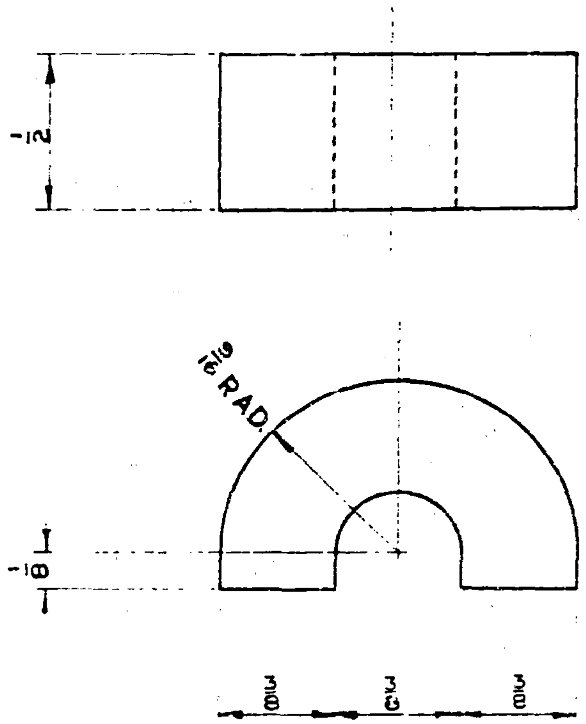


FIG. X DRUM TYPE COUPLING.



MAGNET A. (ALCOMAX)



MAGNET B (ALCOMAX)

FIG. XI MAGNETS FOR DRUM TYPE COUPLING

	H.E.S. C.D.E.E. PORTON	PORTON TECHNICAL PAPER Nº 582	P 2592 DATE 13.12.5?

7

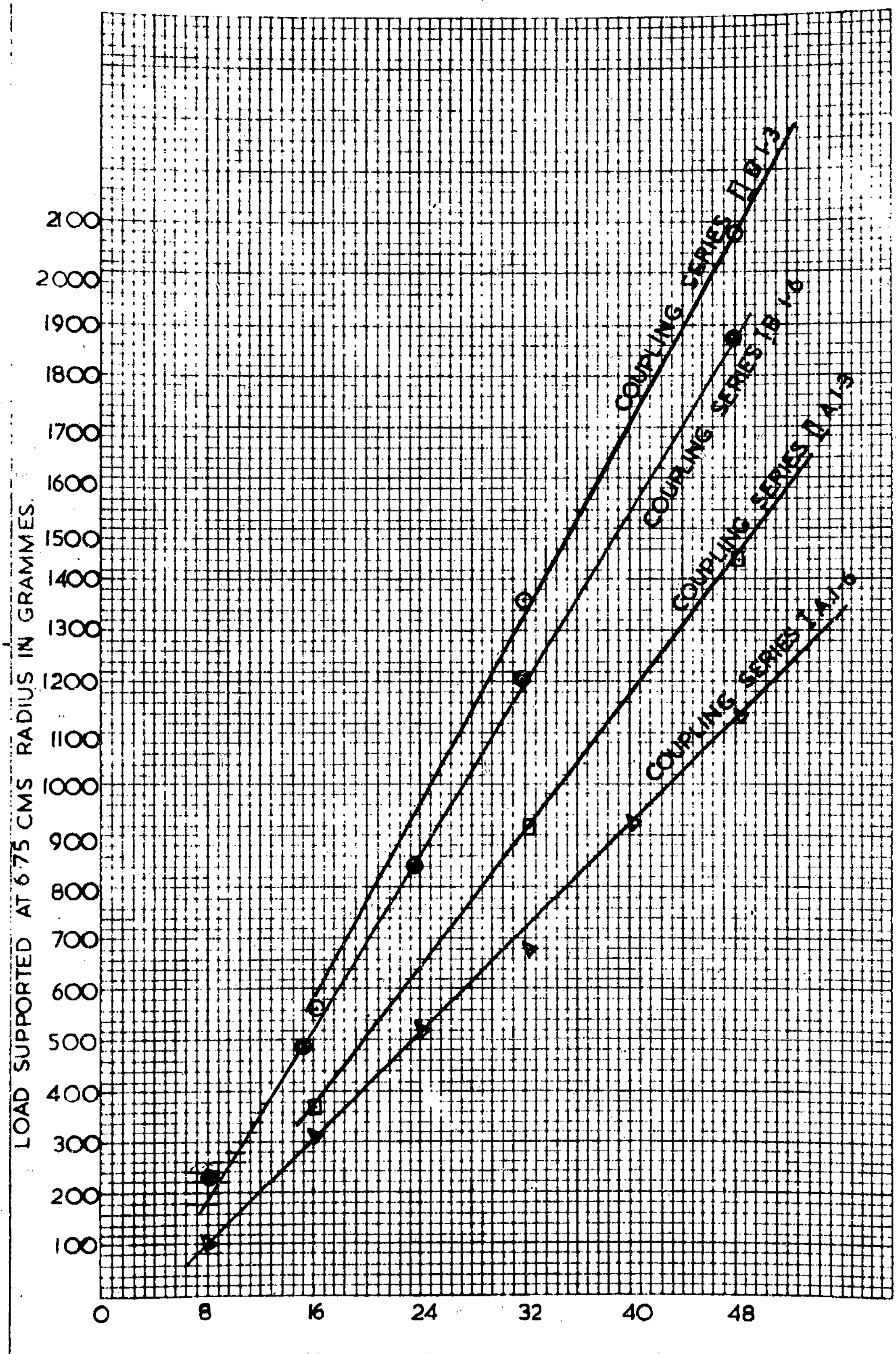


FIG XII LOADING CURVES FOR EXPERIMENTAL COUPLINGS.

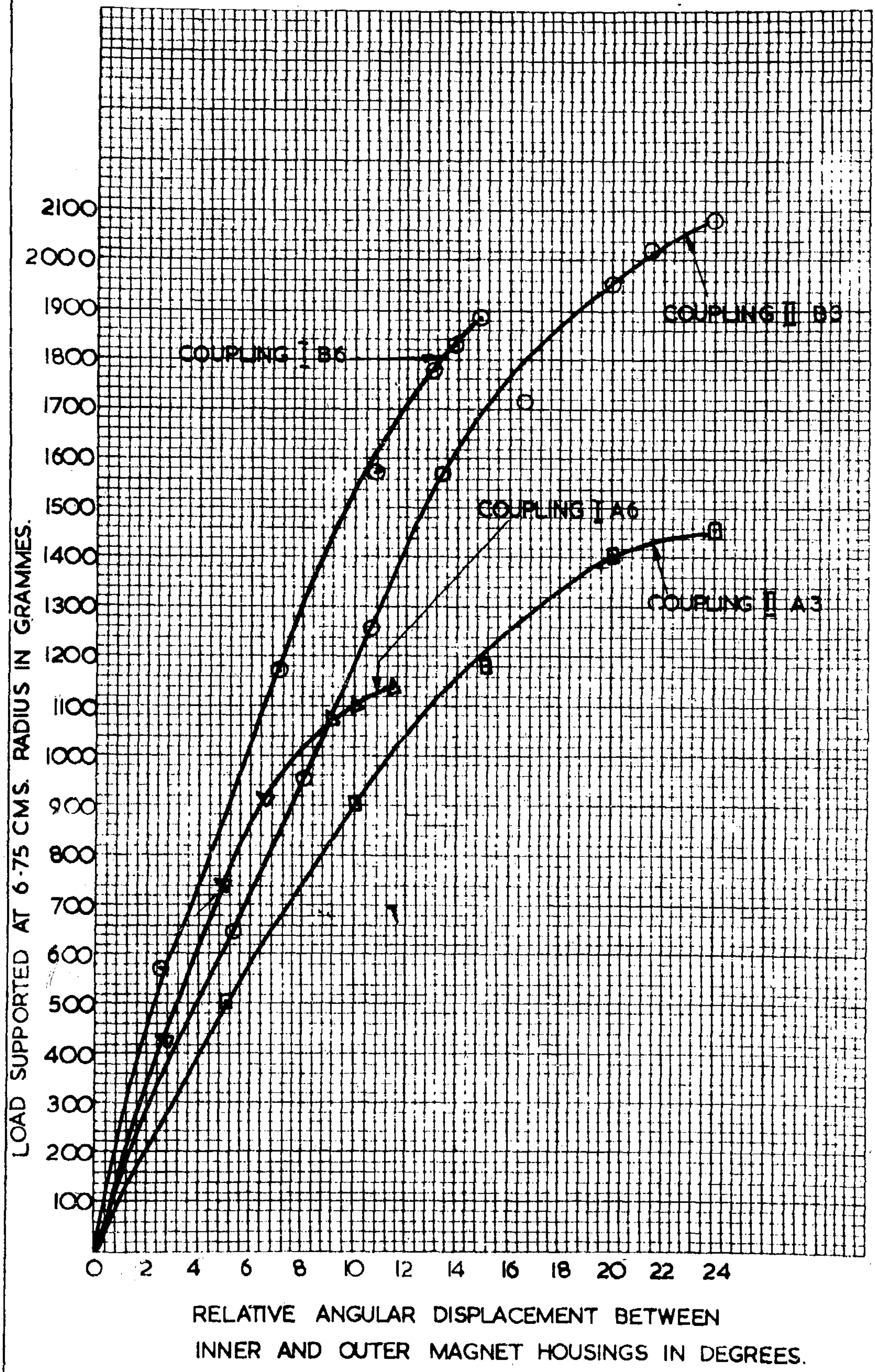


FIG. XIII LOAD / DISPLACEMENT CURVES.

TC. CK	H E S C.D.E.E. PORTON	PORTON TECHNICAL PAPER Nº 582	PT 2903 DATE 24. 5. 56.

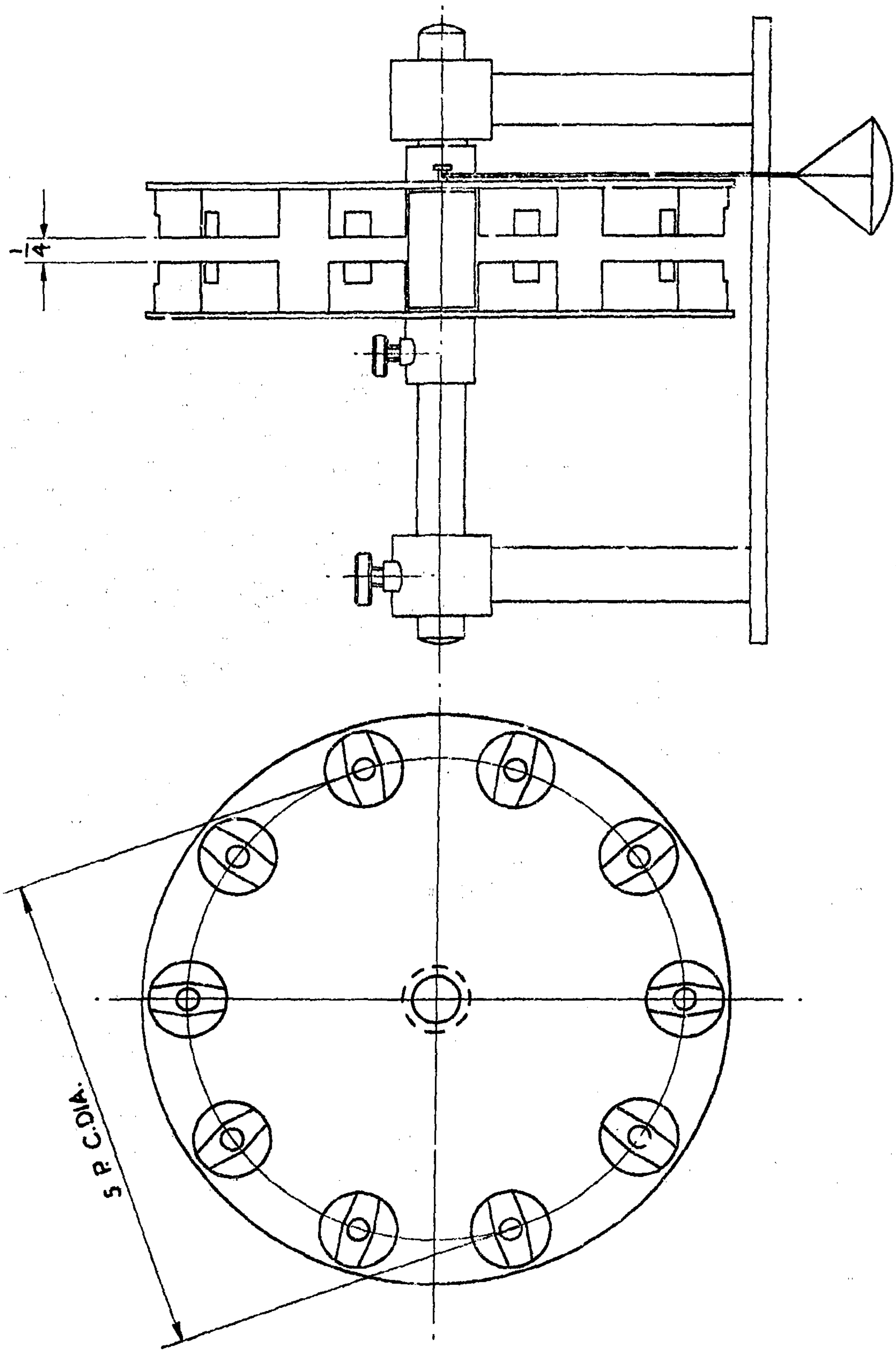


FIG. XIV EXPERIMENTAL DISC COUPLING.

Information Centre
Knowledge Services
[dstl] Porton Down,
Salisbury
Wilts
SP4 0JQ
22060-6218
Tel: 01980-613753
Fax 01980-613970

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road, Suit 0944
Fort Belvoir, VA 22060-6218
U.S.A.

AD#: AD0128070

Date of Search: 17 Jun 2009

Record Summary: WO 189/905
Title: Permanent magnet couplings for glandless rotary drive
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) PTP 582
Held by The National Archives, Kew

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